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35
Commercial Developments

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The last 10 years witnessed the transition of synthetic lubricants from a niche segment of some industrial applications to a mainstream segment of the whole lubricants industry. It is now impossible to discuss the international lubricants business without including a discussion of synthetic lubricants.

The first commercially used synthetic lubricants were silicones, developed by Dow Corning and General Electric in 1943. Then followed polyalkylene glycols, in 1945, developed by Union Carbide, diesters in 1951, phosphate esters in 1953, and polyol esters in 1963. Many of the early applications for synthetic fluids were in U.S. military equipment, notably gas turbines, hydraulic systems, and instruments. Demanding service conditions required higher levels of performance than were possible when conventional mineral oils were used, even with performance-enhancing additives.

Amsoil Corporation introduced the first API-rated fully synthetic engine oil in 1972, although Agip had launched a part synthetic motor oil, Sint 2000, in Italy in 1969. Mobil 1 was launched as the first worldwide fully synthetic engine oil in 1977. When this product was launched, Mobil claimed that it improved fuel economy, reduced oil consumption, allowed faster cold weather starting, kept engines cleaner, and provided better engine protection.

Synthetic lubricants are now used in more than 70 applications, in gasoline and diesel engines, aviation and industrial gas turbines, gear and transmission systems, compressors, hydraulic systems, heat transfer systems, air conditioning, metalworking fluids, food contact industries, and greases. While the higher cost of synthetic fluids was formerly perceived as a barrier to their wider use, it is now more generally accepted that the performance benefits provided often outweigh the higher cost, particularly in applications for which higher lubricity, lower volatility, better biodegradability, lower toxicity, or wider operating range are important factors.

As a result, it is now recognized that, while overall worldwide demand for lubricants is

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likely to remain relatively static, demand for synthetic lubricants is likely to increase at between 5 and 7% per year. This inevitably means that demand for mineral oil based lubricants is likely to fall over the next 5–10 years.

I. THE STRUCTURE AND SIZE OF THE LUBRICANTS BUSINESS

A. Lubricant Supply and Demand

Worldwide production and consumption of lubricants in 1997 was around 40.5 million metric tons, almost unchanged from the 40.3 million metric tons consumed in 1996. Analysis of total lubricant consumption by region for 1997 is shown Table 1. The major producers and users of lubricants are in North America, Europe [west, central, and east, including the former Soviet Union, the Commonwealth of Independent States (CIS)], and Asia. While North America and Europe are two of the largest consuming areas, they also export significant volumes of base oils and finished lubricants to Central and South America, Africa, and Asia. Consumption of lubricants in Asia fell in 1997, for the first time in over 10 years.

The relative constancy of world demand for lubricants in recent years has, however, been masked by some wide regional variations, with significant declines in demand in western Europe and in central and eastern Europe (which includes parts of the CIS), being offset by significant increases in demand in Asia and in Central and South America. From 1990 to 1997, demand in North America first declined and then recovered, while demand in the Middle East, Africa, and Oceania has remained relatively static.

Unfortunately, lubricant base oil production capacity, shown in Table 2, vastly exceeds current demand by around 8.0 million tons, or 20% of demand. Significant overcapacity to produce lubricants exists in western Europe, central Europe, the CIS, and North America. There is some overcapacity in the Middle East, Central and South America, and Oceania, while there is undercapacity in Asia and Africa.

The imbalance between supply and demand is, however, not as bad as the data suggest. Obviously, not all the potential capacity to manufacture base oils is currently being used. Overall, and on average, supply should roughly match demand worldwide, even if it does not do so on a regional basis. Otherwise, the world would, by now, have a huge stock of unused and unwanted base oils. Unfortunately, the potential for vast oversupply is a constant limitation on the prices of base oils.

Table 1 World Lubricants Consumption: 1992–1997

	Annual consumption (metric tons × 10^6)					
Region	1992	1993	1994	1995	1996	1997
Western Europe	5.13	4.88	5.04	5.17	5.20	5.22
Central and Eastern Europe	8.76	8.97	8.28	8.40	8.53	8.66
North America	9.57	9.67	10.09	10.14	10.19	10.24
Central and South America	2.14	2.08	2.17	2.22	2.28	2.34
Middle East	1.46	1.47	1.48	1.49	1.51	1.52
Asia	8.62	8.63	9.55	9.93	10.33	10.23
Oceania	0.52	0.51	0.52	0.53	0.54	0.54
Africa	1.52	1.71	1.73	1.75	1.76	1.78
Total	37.72	37.92	38.86	39.64	40.34	40.53

Source: Pathmaster Marketing.

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Table 2 World Base Oil Production Capacity: 1996

Region	Number of plants	Capacity (tons × 10^3/year)	Share (%)
Western Europe	27	8,130	16.8
Central and eastern Europe	34	11,050	22.8
North America	32	13,820	28.5
Central and South America	12	2,970	6.1
Middle East	6	1,870	3.9
Asia	36	8,630	17.8
Oceania	6	1,100	2.3
Africa	8	970	2.0
Total	161	48,540	100.0

Source: Pathmaster Marketing.

As a result of the present slow growth in demand due to and following the recession, the general oversupply situation in lubricant base oils is likely to be with us until the end of the decade. Additional base oil capacity is most likely to be built in Asia and the Pacific, in the Middle East, and in South America. The lack of growth is due to improved technology, which keeps extending the operating lifetimes of lubricants, reducing demand as fast as new markets appear.

In the industrialized countries, there is major reluctance to close down profitable base oil production units, and indeed a desire to enhance the capability of existing plants, by investing in unconventional base oil production. It is notable that BP, while closing the fuels sections of both the Llandarcy and Dunkirk refineries, kept the lubricants units open. The new European Mobil/BP lubricants business unit, however, decided to close the Llandarcy lubricants refinery. Nynas has expanded output at Nynasham with a new hydrogen unit. Kuwait Petroleum (KPC) at Rotterdam has completed a major revamp.

A very important development in lubricant base oil supply has been the rapid expansion since 1992 in the production of very high viscosity index (VHVI) base oils. BP was the pioneer, producing base oils with VIs higher than 120 from fuel hydrocracking residues at the Lavera refinery in France during the early 1970s. Shell developed a wax isomerization process at Petit Couronne, also in France, to produce VHVI base oils with VIs around 140. Esso at Fawley in the United Kingdom built a wax isomerization plant in 1991, although it is currently still shut down following a major problem in 1994. Since 1992, the number of companies making VHVI base oils has steadily increased to 16 at present, including Mobil, Total, Neste, DEA, Mogul, Mitsubishi, Nippon/Caltex, and Yukong. The most recent additions to this list, in 1996 and 1997, have been the four new VHVI base oil producers in North America: Petro-Canada, Conoco/Pennzoil, Chevron, and Star Refining. In total, VHVI capacity is likely to be around 325,000 metric tons in western Europe and around 550,000 metric tons worldwide by the beginning of 1998.

B. Business Structure

The worldwide lubricants business was dominated until the end of the 1960s by a small number of international oil companies, primarily Shell, Exxon, Mobil, Texaco, and BP. In the 1970s the oil business was rocked by the two oil crises and the rise of state oil companies, of which there are now over 100, worldwide. In response, the majors refocused and reorganized, and are now emerging again as both technical and marketing leaders.

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Key trends that affected the lubricants business in the 1980s and 1990s were as follows.

A continued high level of competition
Increased commitment by the majors to both the base oils and finished lubricants businesses.
Concentration of lubricant businesses into managed profit centers, mainly by the majors, leading to higher efficiency and global product launches
Rationalization of blending plants and improvement of plant efficiency and quality control, such as required by BS5750/ISO 9000
A reduction in the number of independents in the market; smaller blenders being acquired, plus product line exchanges
Stronger emphasis on marketing and distribution; advertising, packaging, brand differentiation, and use of effective sales channels
Continued interest by chemical companies in the lubricants business, as suppliers of additives and synthetic base oils
Demands by automotive, aviation, and industrial equipment manufacturers for enhanced performance levels, leading to the wider use of synthetics and production of VHVI base oils
Environmental issues, from toxicity of additives through disposal to biodegradability

Lubricants markets have always been extremely competitive. The independents and sector product specialists have generally sought business at the expense of the majors, either on price or performance grounds. The lubricants business was originally targeted by the majors as a profitable outlet for lubricant base oils, at prices approximately twice those of crude oil. The key problem in lubricants profitability has always been the majors' continued willingness to sell base oils on the wholesale market (i.e., to their competitors) because they could neither control the overall market nor consume their own base oil production completely. Additionally, additive companies have been either separate companies, joint ventures, or separate profit centers, and they have been willing to provide their R & D expertise to all their customers.

The results are obvious. The independents, with their lower overheads, have usually been able to undercut the majors' prices, so that profitability on the average finished lubricant has always been under pressure. Contrary to general belief, the majors do not usually subsidize the transfer prices for base stocks within their own companies, but try to charge realistic, arms-length prices. These are comparatively easy to set (and hard to challenge) when a market in base oils demonstrably exists. These transfer price rules are occasionally broken—for example, if a significant tender is being bid and the volume is considered vital to the interests of the major.

Historically, the profitability of base oil manufacture has been relatively easy to maintain. As happened in both 1974 and 1980, feedstocks can be diverted to refinery cracking units until "shortages" force the prices up. This is a self-adjusting mechanism, quite familiar to supply managers, and linked to visible markets, such as Rotterdam. Lubricant feedstocks provide attractive yields of gasoline and middle distillates and are premium stocks for use in catalytic cracking units.

Another problem affecting profitability is the high servicing costs of the business, in terms of skilled manpower. Although the representatives of original equipment manufacturers (OEMs) can be justified by the majors and the additive companies, at the other end of the marketing chain, the lubrication survey done by field engineers is an expensive exercise, tying up a specialist for two or more weeks on a single customer report.

Nevertheless, despite all these problems, the majors and large independents remain heavily committed to the business and are concentrating their efforts. Shell now has separate business

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streams for lubricants, a key factor in their international launch of Helix. Mobil has been able to coordinate the international promotion of Mobil 1, and Esso has launched Ultra internationally.

Blending plants have always suffered from low productivity and high inventories, as a result of random customer ordering and the wide range of products on offer—1000 or more per plant. The availability of computers and automated blending has allowed companies to install the latest technology, to close down old blending plants, to increase throughputs, to decrease off-specification production, and to increase overall profitability. Supply chain management techniques are now being applied to lubricants blending, packaging, and distribution.

These strategies are being adopted by the independents, which are also now acquiring other independents, to increase volumes prior to rationalization. Century Oils (now part of Fuchs) installed the latest blending technology. Hunting Lubricants acquired six or seven companies, including Filtrate, ROC, and H. G. Allcards, in the last two years, before themselves being bought by Carless, which in turn was bought by Kuwait Petroleum. Oleofiat formed a joint company with Fuchs of Germany, whereby its motor oil brands (Valvoline and Oleoblitz) went to Oleofiat, and Fuchs Lubrificante took over Oleofiat's Industrial Division. Cepsa, one of the three major lubricants marketers in Spain, has now been taken over by ELF. The remaining 50% of Nynas of Sweden, already owned 50% by PdVSa, was acquired by Neste Oy. Thus two state-owned companies now control this former independent. Castrol acquired Id's Tribol specialty lubricants business in 1993.

Another interesting development in the supply of lubricants in the 1990s has been the privatization (or part privatization) of former state-owned oil companies in several countries. These include Repsol in Spain, some of the petrochemical subsidiaries of ENI in Italy, Petro-Canada in Canada, and Yacimientos Petroliferos Fiscales (YPF) in Argentina. It is likely that these developments will be copied in other countries as global supplies of oil and petrochemical products become even more competitive.

Brand differentiation and better marketing techniques are driving the lubricants business worldwide. Packaging to "high tech" levels and widespread advertising have improved and increased brand awareness. Television advertising is now commonplace, as is support for large- and small-scale motor sport, with Grand Prix car racing at the one end of the scale and motorcycle events at the other.

The chemical companies remain very interested in the lubricants business, especially the additives companies, but few of the synthetic base oil producers have moved as far as direct marketing, except Hatco with Anderol, and Union Carbide. Demands for a lower NOACK value by Volkswagen and the Association des Constructeurs Européens d'Automobiles (ACEA) are boosting manufacture of VHVI and synthetic base oils. The U.S. oil market is now lagging behind Europe in terms of product quality specifications and formulations. Low prices and market confusion between 5W-30, 10W-30, 10W-40, and 15W-40 are not helping.

Overall, the changes just outlined are bringing improvements both to the consumer and to company profitability. They will make lubricants one of the most dynamic sectors of the oil business in the 1990s. It is considered that the slimming down, modernizing, and restructuring processes will continue. The independent lubricant companies that survive will need to find ever better ways of doing business. They will need to cross frontiers, and they will have to find those particular niches, like Castrol, Fuchs, Houghton, Croda, and Quaker Chemical, in which they can do something better than anyone else. The majors will survive because of their technology innovation, international base, and strong OEM recommendation positions. The additive companies will survive, and the national oil companies will probably go on expanding, but there will not be room for everyone!

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There are four types of companies in the lubricants business worldwide:

Company type	Number of companies
Blending and marketing companies	1800
Mineral base oil producers	
Conventional base oils	98
VHVI base oils	16
Synthetic base stock producers	58
Additive companies	34

The independent marketing and blending companies are too numerous to list. There are about 400 in western Europe, over 400 in the United States, more than 200 in central and eastern Europe, about 300 in Asia, and probably 400 or more in China. The largest is Castrol, with worldwide operations. Idemitsu-Kosan is the largest in Japan. Fuchs is now number one in Europe if Castrol is counted as an international.

II. DEMAND FOR SYNTHETIC LUBRICANTS

The conventional definition of a synthetic base oil is one that has been chemically synthesized from distinct discrete chemical components. It is, therefore, easy to see that poly(α-olefins) (PAOs) are synthetic because they have been synthesized from ethylene via 1-decene and that polyalkylene glycols (PAGs) are also synthetic because they have been made from ethylene or propylene and alcohols via ethylene oxide and/or propylene oxide. Mineral base oils, on the other hand, are made by physically removing or chemically altering the undesirable components present in vacuum distillation residues derived from crude oil.

These definitions of "synthetic" have, however, been thrown into considerable confusion by Shell's development of the Middle Distillate Synthesis Process, now being used commercially in Bintulu in Malaysia. The process makes paraffin waxes, as part of a process to make very clean diesel, kerosene and other distillates from natural gas, which Malaysia has in abundance. Some of the paraffin wax is now being shipped to Shell's lubricants refinery in Yokkaichi, Japan, where it is converted into VHVI base oils using the company's wax isomerization process. The composition and properties of these VHVI base oils are identical to those of the VHVI base oils produced by Shell at Petit Courrone from crude oil. But, according to the conventional definitions, the Yokkaichi VHVI base oils are synthetic because they are synthesized from natural gas.

Over the past 5 years there has been much discussion among oil, chemical, additive, and lubricant end-user companies about what is synthetic and what is not. Although a definitive conclusion has yet to be reached, a consensus is beginning to emerge that, for lubricants, "synthetic" is a marketing term that helps to define a level of lubricant performance. In the United States, the American Petroleum Institute (API) and the Society of Automotive Engineers (SAE) have decided not to technically define the term *synthetic*, but to define the properties, performance, and manufacturing processes of each type of base oil. For users of lubricants, what is important is the performance and suitability of the lubricant, not whether it has been made by one process or another.

According to some industry analysts, synthetic lubricants, however they are defined, are

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forecast to account for more than 5% of the total lubricants market by 2000. In reality, by the beginning of 1997, synthetic and VHVI-based lubricants already accounted for slightly more than 10% of the European lubricants market, almost 3% of the North American lubricants market, and around 2% of the lubricants market in other regions of the world. Total worldwide demand for synthetic and VHVI-based lubricants amounted to over 1.2 million tons in 1997.

Other chapters in this book have described and reviewed the main types of synthetic fluid and have summarized the volumes of each type of fluid sold each year, so a comprehensive breakdown of the volumes of each type of fluid sold is not attempted here. It is useful to note, however, that the main types of "synthetic" fluid, by market volume, are poly(α-olefins), esters (of all types), polyalkylene glycols, polybutenes and, of course, VHVI mineral oils.

III. ECONOMIC COMPARISON OF SYNTHETIC LUBRICANTS

A. Advantages and Disadvantages of Different Synthetic Oils

Each of the different synthetic oils described in this book has its good points and its poor points. Some good points are better than others, some worse. A number of the more important advantages and disadvantages of each type of synthetic oil are described in the respective chapters.

Whether any specific advantage or disadvantage is important will depend on the application for which the lubricant is to be used. In general, the following broadly advantageous lubricant properties are highly desirable:

Good inherent lubrication properties
Good low temperature properties
Good high temperature properties
Good viscosity/temperature properties
Low volatility
Good stability
Low toxicity

In some applications, an apparently inferior performance might tum out to be a positive advantage. Some examples can be cited:

The incompatibility of some polyalkylene glycols with mineral hydrocarbons enables the former to be used in natural gas compressors.
The thermal depolymerization of polyisobutenes (PIBs) enables them to be used in clean-burning two-stroke oils.
The chemical structure of diesters that gives them poor hydrolytic stability also means that these compounds are readily biodegradable.

The most important consideration in assessing comparative advantages and disadvantages is this: if a specific application does not require a particular performance property, then a synthetic oil that performs well in that respect will not have any added value for that application. Conversely, if the synthetic oil performs poorly, it will not matter for that application.

B. Balancing Conflicting Performance Requirements

The lubrication chemist's task in formulating a cost-effective lubricant to perform a specific function is not easy. In many cases, a large number of performance requirements, some of which

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may conflict, will need to be satisfied. Earlier chapters have described the range of tests available, both standard and specific, under several categories:

User specifications
Laboratory tests
Rig and bench tests
Quality control tests
Quality assurance and acceptance tests

There are literally hundreds of examples of potentially conflicting requirements that may need to be balanced during the formulation of a lubricant. A few illustrations will suffice to explain the problem:

Blending a diester with a PAO to improve the latter's seal swell properties in automotive engine oil tests is likely to detract from the excellent hydrolytic stability characteristics.
Polyisobutenes are very shear stable and can be used to make very good gear oils, but their low temperature properties make them unsuitable for use in outdoor gearboxes in cold climates.
Using viscosity index improvers in conventional mineral oils can be a cheap way to enhance the viscosity/temperature properties, but at the expense of overall shear stability properties.
Water-based hydraulic fluids generally have excellent fire resistance properties, but they cannot be used a operating temperatures much above 60°C or much below about 5°C.
Water-miscible cutting fluids that contain soluble polymer load-carrying and extreme pressure (EP) additives can have lubricating properties close to those of mineral oil cutting fluids, but at the expense of significantly higher monitoring and maintenance costs.

Many experienced users have shown that the task of formulating a finished lubricant is analogous to producing a perfectly round inflated balloon; if you try to push in any small bump on one part of the balloon's surface, another bump is likely to appear somewhere else! Push too hard and the result may not be the desired one.

Successfully determining the correct level of cost-effective performance is usually achieved by obtaining realistic answers to the following questions:

What performance does my customer want?
What performance will satisfy my customer's needs?
How much is my customer willing and able to pay?
Can this performance be achieved at this cost?
What aspects of performance can be sacrificed to meet a cost limit?
Will I still be able to make a profit?

Finding these answers is not always easy. Often, a genuine partnership between lubricant supplier and user is required. Fortunately, with OEMs, industrial, and military users, such partnerships are becoming more usual.

It is particularly important to remember at all times that the only true test of a lubricant's performance is whether it functions satisfactorily for several years in the machinery for which it was formulated. Lubricant specifications, laboratory tests, rig tests, and field trials are useful only as guides or predictors of likely performance in service.

Ultimately, there is no universal shortcut to the dilemma of balancing the conflicting requirements. This is where the expertise, experience, and dedication of the lubricant supplier provide a great deal of added value.

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Table 3 European List Prices for Lubricant Base Oils: November 1997

Fluid	List price ($/ton)	Price relative to 150 SN
150 SN mineral oil	235	1.0
500 SN mineral oil	235	1.0
Brightstock	300	1.3
VHVI mineral oils	700–900	2.9–3.4
XHVI mineral oils	1000–1200	4.3–4.7
Poly(α-olefins)	1450–1550	6.2–6.6
Polyalkylene glycols	2000–2200	8.5–9.4
Polybutenes	950–1750	4.0–7.5
Diesters	1900–3500	8.1–14.9
Polyol esters	1900–3600	8.1–15.3
Phosphate esters	3500–4500	14.9–19.2
Alkylbenzenes	1250–1350	5.3–5.7

Source: Pathmaster Marketing, from industry discussions.

C. Costs and Cost Comparisons

The current (late 1997) costs of mineral and synthetic base oils of various types are listed in Table 3, which also lists their relative costs compared with 150 solvent-neutral (150 SN) high viscosity index base oil. We emphasize strongly that these prices are averaged list prices in Europe for unformulated base oils only; they do not reflect the volume discounts that some suppliers are able to offer their long-term customers.

Will a user of a PAG get nine times the performance compared to a mineral oil? Is a polyol ester eleven times better man a mineral oil or a PAO almost twice as good as a VHVI oil?

Fortunately, these comparisons are *highly misleading*. First, for many applications, mineral oils require large quantities of additives to bring their performance to a satisfactory level. This adds significantly to the total cost. Second, a number of other costs need to be considered when one is attempting to compare performance. These include the following:

Immediate costs	Hidden costs
Base oils	Distribution
Additives and components	Handling and preparation
Formulation	Monitoring
Laboratory testing	Servicing
Rig and specification testing	Collection
Field trials	Disposal
Blending and storage	Marketing
Transportation	
Sales	

A more realistic comparison of cost with regard to performance would focus on the price paid by the user. Although this depends on all the factors identified earlier, it is likely to be a more accurate guide to comparative performance. In these terms, the most readily obtainable price comparisons are those for retail motor oils sold at the pump and in do-it-yourself shops.

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Table 4 Motor Oil Price Comparisons in the United Kingdom and Germany: November 1997

	Price ratio compared to lowest cost product	
Product	U.K.	Germany
Gasoline engines		
20W-50 Mineral oil	1.0	—
15W-40 Mineral oil	1.4	1.0
10W-40 Part synthetic	2.1	1.3
5W-40 Synthetic	3.3	1.7
0W-30 Synthetic	—	2.5
Diesel engines		
15W-40 Mineral oil	1.5	1.0
10W-40 Part synthetic	2.3	1.2

Source: Pathmaster Marketing.

Table 4 shows current average price comparisons for a number of automotive oil types on sale from the major oil companies in the United Kingdom and Germany.

Clearly, the U.K. market believes that a fully synthetic oil will be able to provide 3.3 times the performance of a mineral oil product for certain demanding applications in high performance cars. Conversely, in Germany, the market is willing to pay only 2.5 times the price for the fully synthetic oil, although the basic product is a 15W-40 grade in Germany, while it is still a 20W-50 grade in the United Kingdom.

Many manufacturers of synthetic oils produce tables that attempt to compare the performances of oils of various types in a range of tests. These tables, too, can be misleading. The quoted tests are usually selected very carefully to show the particular manufacturer's product(s) in the best possible light. The use of ticks, crosses, plus signs, and minus signs to indicate good or poor performance is an oversimplification that does not provide qualitative comparisons. Even replacing ticks and crosses with relative numbers does not help much. Is a mineral oil's hydrolytic stability 5 times better than that of a diester? Does a PAG lubricate 2.5 times better than a silicone oil?

The answer usually depends on which test you do and how you measure the result. In any case, the proper answer is found in the comparative overall performance of each of the lubricants in the practical application. Attention to what the customer needs is the key to assessing comparative performance.

IV. DEVELOPMENTS IN THE SYNTHETIC LUBRICANTS BUSINESS

The synthetic lubricants business has been progressing steadily since the late 1970s and early 1980s, when chemical companies became interested in the commercial potential of specialty products that could command high prices. At that time, it was not well recognized that the costs of most synthetic lubricants are tied to the prices of bulk chemical feedstocks such as ethylene, propylene, and naphtha, which in turn are linked to the price of crude oil and natural gas.

It was an unfortunate coincidence that shortages of chemical feedstocks occurred in 1987 and 1988, pushing ethylene and some derivative prices to very high levels and bulk poly(α-olefins) to nearly $2000/ton. As a result of pricing swings, the price ratio of PAOs to mineral

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base oils, for example, has varied between 3.5:1 and 7.0:1 during the 1990s. The lesson has been that the lubricants industry needs to understand the driving forces in synthetic lubricant production and pricing, while the chemical industry needs to understand the economics of the base oil industry, which has remained linked to crude pricing for 30 years. Only the VHVI oils have been able to break this pattern.

Automotive lubricants have seen by far the biggest increase in synthetic fluid use in the 1990s. Increased sales of part synthetic oils led to significant increases in demand for both PAOs and diesters from lubricants blenders. Sales of VHVI oils are booming. The pattern started in Europe in the late 1980s and spread to all regions of the world, as lubricant marketers recognized the commercial gains possible from a "good/better/best" range of automotive engine oils.

Although synthetics have been used for many years in the industrial markets, steady growth is still being experienced for PAOs, PIBs, PAGs and long chain polyol esters, particularly in compressors, bearings, gears, and circulation systems, and for fire-resistant hydraulics and metalworking applications. Esters are emerging as the dominant technology for biodegradable lubricants, as used in forestry, waterways, and construction. Phosphate esters are making a comeback against polyol esters in fire-resistant hydraulic fluids, but the long-term position of polyglycols in brake fluids is uncertain, with the introduction of DOT 4 fluids, which meet specifications of the U.S. Department of Transportation.

Technical understanding of the properties of synthetic lubricants has been increasing for some years. Some applications have been lost by one synthetic, but gained by another. Where demonstrable advantages can be assessed (e.g., in high performance compressors), there is a solid acceptance at all levels, from OEMs, lubricant companies, and customers. This is the key to success. If any of the three elements of consensus is missing, mere is only disappointment and frustration. The market penetration of synthetic fluids received a major boost in the 1980s from the introduction of the NOACK volatility test and is now receiving a second boost from biodegradability and toxicity issues, generally summarized as environmental benefits.

Consolidation and focus also have begun to emerge in the synthetic lubricants business. Hatco purchased the industrial synthetic lubricants business of Hüls, including the Anderol, PQ, and Aosyn brand names, in September 1996. The company then purchased Royal Lubricants, the aviation and military lubricants business of Shell Oil, in November 1996. Hatco, which has manufactured and marketed ester fluids for many years, announced that it will operate its synthetic industrial lubricants business under the Anderol brand and its aviation and military synthetic lubricants business under the Royal brand, for the foreseeable future.

Amoco Chemicals purchased the PAO business of Albemarle Corporation in January 1996. Albemarle had decided to focus on its core α-olefins business, while Amoco had recognized that PAOs would be a strategic fit with its lubricants business. In the early 1990s, no oil company that manufactured VHVI oils had a chemical division that made PAOs or esters, while no chemical company that manufactured PAOs or esters was owned by an oil company that made VHVI base oils. By the end of 1997, this situation had begun to change radically. Now, Mobil Oil makes VHVI base oils and Mobil Chemical makes PAOs, as do Neste Oil/Neste Chemical and Chevron Oil/Chevron Chemical. Uniroyal Chemical also announced a progressive 50% increase in its high viscosity PAO manufacturing capacity in July 1996, in response to increasing market demand.

The performance advantages of synthetic lubricants are becoming understood and accepted by the market, and synthetic fluids are becoming integrated into the strategic business plans of the majority of lubricants manufacturers and marketers. These are significant commercial advances from the situation only a decade ago, and the trend is unlikely to stop now.

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V. END-USE MARKETS FOR SYNTHETIC LUBRICANTS

The range of current and potential applications for synthetic lubricants is huge. To cover the subject systematically, we group the applications into the following areas:

Automotive lubricants
Compressor oils
Turbine and hydraulic oils
Gear, circulating, and process oils
Metalworking fluids
Other industrial lubricants
Greases
Aviation lubricants

In total, within these sectors, some 70 end uses for synthetic oils have been identified. In certain applications, only synthetic fluids are used, primarily as a result of some performance limitation or other demonstrated by conventional mineral oils. These applications include automotive air conditioning units, brake fluids, a number of different types of gas compressor lubricant, fire-resistant hydraulic fluids, electrohydraulic fluids, aviation gas turbine oils, electrical cable oils, chain lubricants, and aviation greases. In most other markets, synthetic fluids are used for the demanding, high performance applications in which the performance of mineral oils is inadequate.

A. Automotive Lubricants

1. Gasoline and Diesel Engine Oils

The main feature of the markets for gasoline and diesel oils from 1994 to 1997 has been the ongoing effort by most companies to upgrade their top tier oils to 0W-30 or 5W-40 in Europe, while the bulk of the demand remains with 10W-40 and 15W-40. There is a confused mixture of multigrade oils in the United States, with 10W-30 dominating and 10W-40 and 15W-40 in roughly equal proportions; sales of 5W-30 are at about 25% of the average level of 10W-30. Fully synthetic 5W oils have now been introduced widely in many countries in western and central Europe, Asia, and South America. 0W oils have been introduced in Germany, the United Kingdom, France, and other European countries by Castrol, Mobil, DEA, Aral, and others.

Much has been written and discussed concerning blenders' specific options to produce high performance 0W-30, 5W-30, 10W-30, and 10W-40 oils, but these options boil down to poly(α-olefins), esters, or VHVIs, as a partial replacement for the light mineral oils in the formulation. The requirement in Europe is to pass the NOACK test (now at 13% with VW and ACEA A3-96), but increasingly, oxidation stability is also regarded as significant. The VHVI grades are excellent in this regard, and almost all the major European passenger car motor oil (PCMO) marketers are using VHVI base oils in their premium grades.

Mobil is mainly promoting the fully synthetic Mobil 1 (now a 0W-40 oil in Europe) and Castrol has introduced Castrol RS (a 10W-60 oil!), which is another full synthetic. Esso, with Ultron (fully synthetic 5W-50) and Superlube EX2 (part synthetic 10W-40), also is using PAOs as a synthetic component. The most recent introductions in Europe are API SJ/CE classification oils, of which there are several being marketed: Mobil 1, Castrol Ecotec (0W-30) BP Visco 7000 [5W-40 "synthetic," based on "special hydrocracked technology" (LHC)], DEA Ultec (5W-40), Statoil Lazerwey (5W-40), Duckhams QS (5W-40, also described as using a "unique

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manufacturing process"), and Exxon Ultron. In January 1996, Porsche announced that Mobil 1 is the factory-fill oil for all its cars and is also being recommended throughout its worldwide dealer network.

A number of less well known marketers, such as Beverol and some French independents, including Motul, Hafa, and Unil, are known to be using fully synthetic PAO-based oils. Overall, 1990–1995 was a vintage period for PAO, and the total market exceeded 100,000 tons/year, for the first time, in western Europe, including industrial sales.

As the total market expands, it appears that part synthetics are slowly winning over full synthetics, and in this area PAO is still seen as the major component, but competition from diesters is increasing. In the United States, the combination of lack of a uniformly accepted volatility test, very low oil pricing, and widespread acceptance of cheap oil, changed often at "quick lube" outlets, has allowed moderate quality oils to dominate the market. Between 1992 and 1996, marketers began to introduce new fully synthetic products, lead by Castrol Syntec (5W-30), Pennzoil Performax (5W-30), Conoco Xtreme (5W-30), Quaker State Synquest (5W-50), and Amoco Ultimate (PAO/ester). Valvoline recognized the marketing importance of fully synthetic oils when it renamed its "High Performance Synthetic Motor Oil" as SynPower 10W-30 in October 1997.

As North American lubricant marketers slowly began to recognize the benefits of the European "good/better/best" strategy, an increasing number of part synthetic engine oils were launched. Amalie (then a Witco brand, now owned by Sun) introduced the Synplus range of part synthetic oils (5W-30,10W-30, and 10W-50) in February 1996, which promoted low volatility and greater wear protection on start-up. The range included Synplus 2T, a 20W-20 part synthetic two-stroke oil. Valvoline also launched Durablend 10W-30, a part synthetic oil, in February 1996. The Durablend line includes a gear oil, a grease, a two-stroke oil, and a power steering fluid, all part synthetic. Even Castrol had to accept the need for a part synthetic engine oil in the U.S. market, launching Syntec Blend in October 1995.

Part synthetic heavy duty diesel engine oils (HDDOs) have become widely available in both Europe and North America in recent years. Dryden Oil introduced FuelMax 10W-30, a part synthetic, PAO-based HDDO in August 1996. The oil had been extensively road-tested by Southwest Research Institute and compared with a 15W-40 mineral oil HDDO, against which it had demonstrated a consistent 2% minimum improvement in fuel economy. (The maximum fuel economy achieved was over 6%.) Dryden promoted the oil for its fuel saving, noting that 42% of a typical fleet operating cost is fuel, compared with 1% for lubricants, 5% for types, and 12% for parts and repairs. Shell launched Rotella SB (synthetic blend) 10W-30 and 10W-40 in January 1998, claiming better cold cranking and pumpability, improved soot control and oxidation stability, better fuel economy, lower valve train wear, and longer drain intervals for both oils. However, a number of diesel engine OEMs continue to recommend 15W-40 oils because they believe that 10W-30 oils are "too thin" and have "unacceptable levels of volatility" for extended drain intervals.

At present GM is against the NOACK test, and Ford uses the procedure of the American Society for Testing and Materials (ASTM), but may switch to NOACK. There is an MVMA Simulated Distillation Test (ASTM D-2887), which specifies 20% volatility. Ford thinks a 17% requirement will come in soon. These volatility limits are being discussed as part of the debate about the new GF-3 specification of the International Lubrication Specifications Committee (1LSAC). There is also a GM high temperature/high shear test for the Chevrolet Corvette, with a 9% oil volatility requirement. The net result is that sales of PAOs, esters, and VHVI base oils in the U.S. branded automotive lubricant market totaled only 54,000 tons in 1996, while in Europe about 348,000 tons were used.

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2. Motorcycles and Outboard Engines

In general motorcycle and competition two-strokes use mineral oils blended with either esters, polybutenes, or PAOs, which are vying with each other for different sectors of the market. A number of companies are making strong efforts with competition two-stroke engine oils, notably Castrol, Rock Oil, Silkolene, P. J. Harvey (U.S.), and Putoline (the Netherlands). Additionally Bel-Ray, the U.S. market leader, and Bardahl are marketing synthetics to the general motorcycle market. Petrofina remains a strong long-term marketer of general two-stroke oils based on polybutenes.

Motorcycle lubricants are seen very much as a specialist niche for synthetics, since most lubricants are sold through specialist shops. The change in the form of retailing, coupled with the idea of motor bikes as sporting, or "fun" machines, rather than transport, has changed the demand for lubricants and the perception of lubricants. The majors have responded, and Shell, for instance, is offering VHVI-based motorcycle lubricants, which are sold at most of its service stations as well as motorcycle outlets; the brand name is Quattro. Castrol has launched synthetic motorcycle lubricants based on esters, under the names Castrol 545 and 747.

Modern outboard two-stroke engines have evolved into sophisticated units. These are often multicylinder units with advanced oil injection systems, electronic ignition, and engine capacities of over 3 liters. The Evinrude Euro 4 Engine test has been used to study lubricity. The connecting rod plain bearings in the engine are particularly sensitive to lubrication quality. Test work has shown that normal mineral-based lubricants of Boating Industry Association (BIA) TC-W quality pass at 50:1 but fail at 100:1 because connecting rod bearing lubrication is inadequate. In contrast, synthetic-based lubricants have been demonstrated to extend the fuel oil ratio to 100:1 and, in some cases, even to 150:1. Outboard motorboat engine oils have also been moving steadily from mineral oil bases to diesters in Europe, to meet environmental concerns with respect to water pollution. The biodegradability test for this, modified, is the Coordinating European Council's CEC-L-33-A-94.

3. Transmissions and Gearboxes

In the automotive manual transmission and axle oils sector, SAE 75W-90 is only slowly finding favor. Mobil now even has this on general sale in smaller packs in Europe. For heavy duty, the mainly polybutene-based SAE 80W-140 grades are still selling well. Users of SAE 75W-90 or 80W-140 gear oils are said to save between 4 and 10% on fuel consumption. The use of these grades, when based entirely on mineral oils, has reportedly led to rear axle wear problems. This problem has been eliminated by the incorporation of 20–25% of esters into the formulation of 75W-90, and a patented PIB from Lubrizol into the 80W-140 formulation. (The Lubrizol product is considered here to be a part synthetic, rather than an additive package.) Mobil's 75W-90 is fully synthetic, as is Nyco's and others in Europe. Shell and Esso sell similar products in North America.

According to Castrol, lubricant oil temperatures at high speeds can be 30°C cooler with a synthetic oil. In the U.S. Eaton Axles issued new Road-Ranger specifications for full synthetics in July 1996. In the heavy-duty gear and transmission systems of class 8 trucks, after the first oil change (3000–5000 miles) the fluids can be run for up to 500,000 miles without changing, giving real cost benefits to users. Eaton regards these systems as "filled-for-life" and believes that the next improvement will be "sealed-for-life," which will definitely require synthetic oils.

Part synthetic 80W-90 heavy-duty gear oils were introduced in North America in the last few years. Texaco launched Multigear SS early in 1996, followed by Unigear SS from Century Lubricants. A number of other companies are selling similar products.

Peterbilt Motors, a large U.S. builder of trucks, began using fully synthetic gear and transmission oils as factory-fill in all its trucks in April 1996. Peterbilt uses mainly Eaton and Rock-

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well gear and transmission components, and has been a major supporter of Eaton's extended drain and fill-for-life policies associated with the use of synthetic lubricants.

Demand for SAE 75W-90 rear axle oils is expected to grow. The attitude of the original equipment manufacturers is critical, inasmuch as the majority of vehicles now have filled-for-life transmissions. The market for 75W-90 is already strong in Scandinavia, with its severe winters. In the past, axle oils have been frozen solid, when engines were still able to start. The annual U.S. demand for axle oils and gearbox fluids is around 15,000 tons, for both cars and trucks. At present, sales of synthetics are between 3000 and 4000 tons per year, mainly 75W-90 for trucks, as well as cars.

4. Automatic Transmissions

A number of car manufacturers are now seeking "filled-for-life" automatic transmissions, to increase customer satisfaction and to assist with further improving vehicle fuel economy. This will be derived from "shudder-free" torque converter clutches and stable friction characteristics in the automatic transmission fluids. The demand for "filled-for-life" will require significant improvements to ATFs. Antiwear requirements will need to last for 100,000–150,000 miles, and the oils will need to have exceptional high temperature–viscosity properties combined with good low temperature–fluidity properties and high shear stability in pump and clutch tests. Obviously, foaming resistance, air entrainment, and material compatibility (elastomers, bearing materials, and friction materials) will need to be at least as good as or better than currently. As a result, there will be a heavy dependence on base oil properties, which probably means the use of VHVIs, PAOs, and/or esters.

Ford's activities toward a MERCON-V specification have continued. ATFs to meet the requirements underwent trials in Europe in 1996 and are now being introduced in North America. However, the primary service fill oil is likely to continue to be one of the current MERCON fluids until the trials have been completed. Although Chrysler delayed development of a new ATF, the automaker now recommends against the use of any fluids that do not meet its MS7176D specification. It is possible that Chrysler's new MS9602 specification will be introduced in 1999.

Following the expenditure of around $3 million by General Motors and the additive companies on new DEXRON-IV oils, this development has been suspended, owing to the cost of the ATFs that met the target performance levels. New, lower performance targets are now being prepared, and it appears likely that the resulting products will contain less synthetic base oil than the earlier products. The requirements for the next GM ATF are broadly the same as those demanded by Ford, and GM's main service fill will continue to be DEXRON-IH until DEXRON-IV is ready, which is reported to be unlikely before 2001.

5. Brake Fluids

Brake fluids represent one of the major existing outlets for polyalkylene glycols. There are two main brake fluid formulations in use in western Europe, both based on specifications issued by the U.S. Department of Transportation (DOT). They are DOT 3 and DOT 4. The formulations differ markedly in polyalkylene glycol content, with much more PAG being used in DOT 3.

Brake fluids have been continually improved, especially in terms of boiling point, starting from the SAE J 7OR3 specification of the 1960s. However, brake fluid has largely become a fill-for-life fluid and is rarely changed. It is now widely recognized that brake fluids deteriorate in service after 2–3 years because of water absorption. In general, the higher the boiling point of the brake fluid, the more hygroscopic the glycols. Boiling points are still trending slightly upward. Typical boiling points in use in Europe are now 220–250°C. The minimum requirement to meet DOT 4 is 220°C.

The DOT 4 fluids are formulated to give greater "in-service" stability, especially with

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respect to water absorption. The formulation of DOT 4 blocks the ether linkage and hydroxyl group, which are vulnerable to moisture pickup.

There has been a major swing to DOT 4 fluids in the last 5 years in Europe, but not in the United States. Naturally this has been reflected in lower sales of PAGs to the formulators. This trend will of course continue to work its way through the car fleet over the next 5–10 years. At the peak, in the mid-1980s, PAG sales were about 12,000 tons for consumption in Europe, but had declined to about 6000 tons by 1996. In the United States there is currently a trend toward lower molecular weight polyglycols.

6. Automotive Air Conditioning

The U.S. market for automotive air conditioning is much larger than all other markets in the world, despite a big increase in the number of new vehicles being sold with air conditioning in many countries, notably in Europe. As a result of the chlorofluorocarbon (CFC) controversy and the Montreal Protocol, new refrigerants are being introduced, notably R134A. The compatible synthetics seem to be either polyglycols or polyol esters, with PAGs currently dominant.

In January 1996 Castrol introduced a polyol ester lubricant, Retro A/C for R134A or R12 air conditioning systems in light and heavy trucks and off-highway equipment. U.S. sales of synthetic oils for air conditioning systems totaled 3000 tons in 1996, with 1000 tons for GM, about the same for Ford and Chrysler combined, and 500 tons for other manufacturers, such as the Japanese.

7. Automotive Greases

PAO- and ester-based greases are being used for automotive purposes, but the bulk of the market remains with conventional products, such as lithium-based greases. However, in western Europe, concern expressed for the environment, with particular emphasis on buses and trucks equipped with automatic grease applicators, is leading to the adoption of polyol ester based greases, using long chain (such as C_{18} oleic acid) technology. At present this market for biodegradable greases is in its infancy, having really begun in 1990, but it is growing.

B. Compressor Oils

Because of the wide range of gases and compressors in service, the market is complex. We describe below the main gases, the types of compressor, the competing synthetic products being sold for each end use, or the uses for which only one synthetic has proved satisfactory.

The total demand for compressor lubricants in western Europe is around 50,000 tons. As an order-of-magnitude estimate, it is believed that total synthetics sales are currently in the range of 15,000 tons. There is now competition from VHVI mineral oils. At least a similar volume is used in the United States, where VHVI competition is not so strong. A volume of 4000 tons of PAGs is known to be used in chemical, carbon dioxide, helium, and carbon dioxide compressors. The United States of course has a large network of natural gas pipelines and substantial capacity for gas production.

1. Air and Gas Compressors

The industrial market covers a wide range of compressor types and the compression of air, oxygen, helium, natural gas, liquid petroleum gas (LPG), ethylene [to make low density polyethylene (LDPE)], and ethylene vinyl acetate.

In these compressors, the main problems of lubrication now center around the need for high oxidation stability of the lubricant, to resist degradation and deposits at increasing discharge

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temperatures, as well as the need to accommodate the problems of cross-leakage between oil and air (or gas). In the case of oxygen compressors, such leakage could lead to an explosion. In the case of ethylene compressors, used in the manufacture of LDPE, the need is for a lubricant meeting food and drug regulations, since LDPE products are often in contact with food.

The compressor market is changing technically, with a general trend to higher discharge temperatures on reciprocating compressors and, in addition, a move away from reciprocating units toward vane and screw-types. For reciprocating compressors, following investigations into explosions due to the formation of deposits (and subsequent blockage) in the discharge pipes, new lubricant specifications, calling for low carbon forming oils, have been widely accepted. The Pneurop oxidation test (POT), a safety rather than a performance test, is one of these. "Heart cut" mineral oils with high VI and molecules of the same size, are being used to satisfy these tests. Mineral oils are satisfactory for discharge temperatures up to 220°C. Synthetics are also being used, including PAGs, PAOs, diesters, and polyol esters. PAO ester blends have proved the most widely accepted products in the U.S. market, with a very high share of the total business. Ingersoll-Rand has proprietary formulas based on esters. Additionally PAGs are being used in Ingersoll-Rand and Sullair compressors. Sullube 32 from Sullair is a PAG rebrand.

In oil-flooded, screw-type compressors, the oil circulates in the compressor and acts as both lubricant and coolant, coming out with the airstream, through the air receiver and filter pack, to return to the compressor. Residence time is important. Encapsulation of the compressor to reduce noise adds to the operating temperature. Oil changes are now made annually (4000 hours), instead of quarterly (1000 hours). The lubrication of screw compressors is a growth area for synthetics, and diesters are being widely used, as well as PAO–ester blends. However, VHVI hydroreflned mineral oils are also proving very satisfactory.

In common oil systems, compressors for reinjection of natural gas, or pumping on gas transmission lines, with the pumps usually being driven by gas turbines, sometimes use polyol ester lubricants; many are separate, however, and use PAGs. Shipboard compressors, maintaining gas pressure on LNG/LPG ships, are concerned with gas dilution of the lubricant and subsequent bearing failure from too low an oil viscosity. PAGs are being used for these compressors because of the lower solubility of natural gas in the synthetic lubricant.

Ethylene compressors, making LDPE, also represent a significant market for synthetics. These large compressors, chiefly Burckhardt, Ingersoll-Rand, and Nuovo-Pigone, are now using PIBs, PAOs, and PAGs (sometimes blended with white oils) instead of the white oils and "O" wax formerly used. The synthetics are less susceptible to ethylene dilution, and they also pass the Food and Drug Administration (FDA) requirements. Apart from air compressors, the largest single end use identified for synthetics has been the LDPE compressors, where, for example, PAG sales worldwide are estimated at 15,000 tons: 5000 tons in the United States, 6000 tons in western Europe, 2000 tons in Asia, and 2000 tons elsewhere, including 1500 tons for the CIS.

Oxygen compressor manufacturers are seeking ways of reducing the risk of explosions. Some oxygen compressors of the large, separate cylinder feed, reciprocating type, are tending to use polytetrafluoroethylene (PTFE) coatings and operate "dry," or oil-free. Some are using phosphate esters. Compressors for nitrogen and helium, particularly those used to compress diving gases, generally use PAG-based lubricants.

2. Refrigeration Compressors

Refrigeration compressor oils must lubricate moving parts effectively, while satisfying requirements not demanded of other lubricants. These oils are expected to give many years of trouble-free service, often without replacement or loss makeup, or other maintenance attention. Lubrica-

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tion, of course, is the primary function of a refrigerator compressor oil; it must, in addition, have other properties, for the following reasons:

It mixes intimately with the refrigerant used in the system.
It is carried over in small amounts into the refrigerant lines.
It is in direct contact with the motor windings in hermetic units.
It is exposed to both temperature extremes: high temperatures at the compressor discharge valve and very low temperatures at the expansion valve.

Traditionally these compressors have been lubricated with wax-free naphthenic oils, because of the need for low pour points. Wax separation in paraffinic oils at low temperatures can cause clogging of the expansion valve and lines. In recent years there have been strong commercial efforts made in this market with alkylbenzenes. The alkylbenzenes have good miscibility with fluorocarbon refrigerants such as R22 and R502, and their critical solution temperatures are lower: between −60 and −100°C. Typical low temperature applications entail the production of antibodies, nitrogen peroxide, liquid oxygen, and soluble coffee. The alkylbenzenes can be used in either reciprocating or rotary compressors, including the modern screw type. Blends of alkylbenzene and naphthenic oils are also being marketed, primarily aimed at balanced lubrication properties.

Mobil has been making strong efforts in this area with PAO-based oils. It is expected that penetration of alkylbenzenes and PAOs into this market will increase. Sales in Europe are believed to be about 3000 tons, either to the initial-fill market or for special low temperature industrial applications. The bulk of the market probably will remain with naphthenics in the foreseeable future, but a number of manufacturers are now using alkylbenzenes for initial-fill.

Some of the newer refrigerants, R134A/R125B introduced as replacement for CFCs, are causing difficulties for PAOs, with which they are not compatible. It appears so far that PAGs and esters offer the best solutions.

C. Turbine and Hydraulic Oils

1. Gas Turbines Oils

Gas turbines fall into two main types:

The direct use of aero-derived turbines for electricity generation and mechanical drive applications (compressors and pumps).
Industrial gas turbines, pioneered in the United States by General Electric (GE), but also now developed in Europe by ABB, GEC, and Siemens. These are also used for electricity and cogeneration but are now on a much larger scale than the aero engines. For example, while the Rolls-Royce RB211 aero-engine generates 25 MW, the latest industrial GE Frame 9 "F" produces 210 MW of electricity.

Almost all aero-derived engines operating on oil rigs in the North Sea, or on CIS gas pipelines for pumping, use aero-engine oils (e.g., diesters for Rolls-Royce Avons and polyol esters for RB21 Is). On the other hand, the large industrial gas turbines have tended to use high performance mineral turbine oils. Now, however, there are examples of some using synthetics, based on PAO–ester mixes. In the 1990s the market outlook for heavy-duty industrial gas turbines is exceptionally good, as natural gas fired, combined cycle power stations of high efficiency and moderate capital cost are built in large numbers, in response to environmental pressures. Since privatization, in the United Kingdom alone, about 25 new power stations of 300–900 MW each have been proposed, mainly using combinations of at least two industrial gas turbines and one

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steam turbine. Since 1960, General Electric, the market leader, has shipped over 5000 units of industrial gas turbines.

2. Hydraulic Fluids

Hydraulics represent the largest single end use in the industrial market. Synthetic fluids, however, have really been successfully sold into the fire-resistant fluid sector only. This is the main sales outlet for phosphate esters and a major market for PAGs. Competition comes also from invert emulsions (water-in-oil), particularly in the United Kingdom, and from long chain polyol esters. A key factor in choosing a fluid is the sealing system. For example, it is not usually practicable to switch from phosphate ester to water–glycol, but it is possible to switch from phosphate ester to, say, a long chain polyol ester, such as Quintolubric from Quaker Chemical.

Phosphate esters have obtained a significant market and are particularly strongly entrenched in the steel industry. Phosphate ester sales to the mining industry are for specialized applications, such as continuous miners and hydrokinetic transmissions (fluid couplings), driving coal conveyors, but in Europe not in the United States. Steam turbine governor control mechanisms, which have a small but important market, are designed to ensure shutdown of the turbine in the event of fire. The major problem with the phosphate esters is their toxicity. If carefully handled and used in well-maintained systems, they are satisfactory, but if leakage is uncontrolled, they can be hazardous both to equipment operators and to the environment. As a result, phosphate esters have been losing their market share in recent years, to water–glycol based fluids for new systems and to long chain polyol esters for existing systems, or for applications where mineral oils are being replaced by FR fluids for insurance purposes.

Water–glycol fluids usually contain 35–50% water, 10–30% propylene or ethylene glycol, 30–50% PAG thickeners, and a balanced additive package. Their main markets are for die casting (where they have taken over from phosphate esters), some machine tools, the steel industry, underground mining (for hydraulic motors and hydrostatic transmissions), and the automotive industry (for welding and induction hardening equipment).

Water-in-oil emulsions are still widely used by U.S. steel plants, for hydraulic motors, and for hydrostatic transmissions. However, in the countries of the European Union these emulsions are not considered to have sufficient fire resistance, and in France and Germany water–glycols are used in preference. The steel industry and the automotive industry have used these water-in-oil emulsions, but in general they are losing favor to fluids with better fire resistance. The 90/10 (or 95/5) fluids are basically 5–10% mineral oil blends in water. Naturally they are very low cost, and widely used for nondynamic hydraulic oil uses such as hydraulic rams and pit props. Considerable work is being carried out to improve these fluids with additives and possibly the incorporation of synthetics. U.S. sales of 95/5 or HWB (high water based) fluids were about 3500 tons (as sold) in 1990. Long chain polyol ester based fluids have been achieving significant sales in the mining, steel, and car industries because they combine nontoxicity, ease of inter-changeability with phosphate esters, and a reasonable level of fire resistance. As well as in mining and steel plants, new markets developed include electrostatic precipitators and paper mill hydraulic systems, where there is a fire risk. Food processing plants with a fire risk, such as gas- or LPG-heated chicken farms or dairies, are also now using polyol esters in their equipment.

In summary, the use of water-glycol fluids is increasing, whereas water-in-oil emulsions are decreasing and long chain polyol esters, which had been increasing, are now being replaced again by phosphate esters, which are making a comeback. The future for oil-in-water emulsions remains unclear, even with the use of synthetic oils and improved additive packages.

Annual demand for water–glycol fluids is around 25,000 tons, and for phosphate esters about 4500 tons in western Europe. Polyol ester sales are believed to have reached 2000 tons/year. As yet there does not appear to be any evidence of other synthetics being used. In the

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United States, water–glycol sales as FR fluids were around 24,000 tons in 1996, with phosphate esters and long chain polyol esters each at 5000 tons.

Some highly specialized, but low volume, hydraulic fluids can be grouped together for ease of reference. These include offshore compensators, electrohydraulic controls and governor mechanisms in power stations, and electrostatic precipitators.

Offshore motion compensators are hydraulic mechanisms on floating drilling rigs and drill ships that allow the vessels to move while the drill string remains attached to the seabed and the well riser. In general, fire-resistant fluids are used, since "offshore" is designated a hazardous area, hence must be double-protected. Phosphate esters, PAGs, and long chain polyol esters have been successfully sold on this market.

Similarly, governor control mechanisms in power stations need to be able to effectively shut down the turbines, even if the station is on fire. This is a well-established, long-term market outlet for phosphate esters.

Electrohydraulic controls in power plants, with large (6 ton/2000 gal) reservoirs, proved to be a new outlet for long chain polyol esters in the 1980s. Similarly, electrostatic precipitators, fitted to reduce the dust or solids content of fluids or gases (such as stack gases in power stations), are beginning to use long chain polyol esters, obviously again for fire hazard applications.

"Environmentally friendly," which means biodegradable, hydraulic fluids are also gaining in acceptance, again notably in Europe. One of the first companies to begin marketing these products was Mobil, with its EAL Syndraulic line, introduced in February 1996. (EAL stands for Environmental Awareness Lubricants.) These ISO 32, 46, 68, and 100 hydraulic oils are synthetic ester based, with an advanced additive pack and VIs ranging from 143 to 153. They are able to operate routinely at temperatures between −30 and 95°C. Many companies, including Shell, Neste, Statoil, and Exxon, have introduced biodegradable hydraulic fluids, based on either diesters, polyol esters, vegetable oil esters, and even lower viscosity PAOs.

D. Gear, Circulating, Process, and Functional Oils

Every industrial plant or factory contains gearboxes or bearings. Circulation systems are usually confined to large machinery units, such as the bearing lubrication systems encountered in paper and steel mills. Although PAGs enjoy a broad industrial market, increased usage of synthetic alternatives is expected in the future. PAO and PAO–ester blends are the most likely competitors. It is believed that sales of synthetics in these general gear areas of the industrial market have increased significantly over the past few years, as a result of major sales efforts, especially by Mobil. Total sales in western Europe may be as high as 10,000 tons/year.

Functional fluids may be defined as industrial products that form an integral part of a particular piece of equipment, without which the equipment will not operate, or may suffer damage: heat transfer fluids, electrical insulating fluids, and offshore compensators are good examples. It is important to differentiate functional fluids from process applications, where the product is actually consumed or converted in the manufacture of the final product (e.g., rubber process oils or textile finishes). Some products are very difficult to classify. For example, are drilling fluids functional or process? Are hydraulic fluids lubricant or functional? We have tried, in such cases, to follow industry practices.

1. Circulation Systems

Some circulation systems, such as those feeding lubricant to gearboxes operating paper mill drying cylinders, run at high bulk oil temperatures. Particularly in Scandinavia and the United States, it has been found that PAG lubricants enable the mills to be run faster and at higher temperatures, without deterioration of the lubricant through oxidation. Higher paper output has

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been achieved. Large paper mill manufacturers are now recommending synthetics at start-up. Polypropylene glycol is the most commonly used synthetic base for this application, but PAOs are also being introduced. In low temperature conditions, found in cold storage applications and occasionally in steel works and open-cast mining, alkylbenzenes and PAOs are being used as circulation lubricants.

2. Gears

Various methods are used to apply gear lubricants. Application may be by drip feed, splash, or spray, or by a lubricant bath. Large industrial gear sets, using spur or helical gears operating under moderate loads, are usually lubricated by circulating systems. The heavier viscosity turbine oils are generally suitable for this application. In enclosed systems the temperatures reached may be high enough to necessitate the use of premium oils, with high oxidation resistance. These oils should also possess satisfactory antifoam properties and, if water is present, good antirust and good demulsibility properties. Where higher loadings are encountered in industrial gears, lead, sulfur and phosphorus compounds have been commonly used, to improve the load-carrying capacity of the lubricant. In the last decade more sophisticated compounds have been developed to replace lead, for health reasons.

Synthetic lubricants of the PAG type are finding wide acceptance as industrial gear lubricants. They are particularly suitable for worm gears, because of their lower coefficient of friction. Their ability to lubricate at high bulk oil temperatures, or under heavy loading conditions, has expanded the number of applications. Poly(α-olefins) are also now being used, incorporating a special EP additive package, for oil temperatures in the 50–180°C range. In the United Kingdom, David Brown, Highfield, J. H. Fenner, and Moss Gears have approved PAO-based products.

Thickened oil compounds made from PAG bases have been used successfully for some time in packed-for-life gearboxes. David Brown mass-manufactures small gearboxes without drain plugs, which can, therefore, be mounted in any position. A further advantage of this synthetic compound is that the gearboxes can be shipped for use in any climate, without the necessity to specify different lubricants. In North America, U.S. Electric Motors uses a special PAG-based compound (ISO 220) in filled-for-life gearboxes. Another useful application for PAGs consists of worm gears on externally operating coal pulverizers, where there had once been a need to heat the cylinder oil lubricant by steam coils before start-up. Now, when PAG lubricants are used, these units do not need such elaborate preheating.

3. Bearings

The high pressures encountered on large calender machines, producing rubber or plastics, can result in bulk oil temperatures of over 200°C. Up to about 150°C mineral oils are still used, but for higher temperatures the PAGs have been accepted as the solution. Again, PAOs have also been introduced for this application and even some PAO–ester blends in the United States.

4. Heat Transfer Oils and Solar Fluids

Heat transfer systems and the fluids used in them are complex and highly specialized. The largest volumes are in major circulation systems at chemical or process plants. This business is usually awarded at the initial-fill stage, with sales thereafter only as top-up or infrequent change. It is important to offer technical support at the design and commissioning stage of these large "one-off" systems.

The fluid used is dependent on the heat transfer temperature required. About 45% of the overall heat transfer fluid market is met with mineral oils. The total worldwide market is 50,000 tons/year, and synthetics annually represent about 9000 tons (20% of the total). Thus liquids represent 65% of the market. The balance are high temperature, vapor phase systems (25%) and intermediate temperature systems (10%).

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The main synthetic contenders are polyglycols, silicones, and specialized hydrocarbons. Mineral oils have a tendency to foul, and also have a relatively narrow operating range (≤300°C) and poor thermal stability. PAGs also have some problems of thermal stability and narrow operating range (165–250°C). However, they are in wide use in smaller systems, such as plastic injection molding machines, mobile heat exchangers (for composites), and small chemical reactors. Silicones have high thermal stability and a wide operating range, but poor heat transfer properties. The specialized hydrocarbons, such as hydrogenated polyphenyls (−10 to 345°C), alkyl aromatics (50–300°C), or polyphenyls (75–400°C), are offered to provide the right balance of properties. Monsanto and Dow Chemical are leaders, with the widest range of specialist products on offer. BP, Bayer, Hiils, Castrol, Texaco, Nippon Steel, and Wibarco (with alkyl aromatics) are suppliers with limited product lines. These well-established aromatic compounds, phenyls and diphenyl oxide type materials, are coming under increasing government pressure for control and restriction in the United States. Uniroyal and Amoco Chemicals have been actively promoting PAOs in this market sector, as potential replacements.

Solar fluids for roof-type water heaters are another heat transfer market, which although already in wide use in the United States, Italy, Cyprus, and Israel, are likely to see rising demand in an energy-conscious and "green" world. Low viscosity PAOs (2 cSt), with metal deactivators, are finding outlets as solar fluids.

5. Electrical and Insulating Oils

Naphthenic base oils have traditionally been used in transformers and capacitors, for applications in which fire risk was not being considered, that is, outdoors. The naphthenics were believed to have higher oxidation stability than paraffinics. With their lower wax contents, moreover, the naphthenics' pour points were suitable, on average, for transformers operating outdoors down to −35°C (pour points of −45°C). In fact, special naphthenics have been refined with pour points down to −60°C, but for applications with potential operating temperatures below −50°C, synthetics have generally been used.

Transformers operating indoors have tended in the past to use fire-resistant insulating fluids, such as polychlorinated biphenyls (PCBs). However, under EU regulations, many end users are now prohibited from using PCBs. The EU regulations are not as strict as those that have led to the almost total replacement of PCBs in all applications in Sweden, the country in which their environmental persistence was first recorded in the late 1960s. The total market for PCBs in western Europe is estimated to have been about 2000 tons, of which some 800 tons went into dielectric fluids. A further 900 tons was used by the German mining industry, in conjunction with phosphate esters, for hydrokinetic transmission and other fire-resistant hydraulic uses, underground.

The excellent range of properties exhibited by PCBs as dielectrics is illustrated by the number of products has been necessary to introduce to cover the same field adequately. In general, silicone-based products have been found satisfactory for transformer applications less dependent on electricity-related properties, where the main function is as a heat transfer medium, whereas high voltage capacitor uses have required a range of other products. Silicones and other specialty-type products have probably gained the biggest share of the PCB replacement market. They are particularly suitable for new equipment, which can be designed around the dielectric. Dow Corning has been marketing a polymethylsiloxane product, and silicone-based products are also offered by Bayer and Rhone-Poulenc for transformers.

Other developments in this field have come from GEC in the United Kingdom, whose Micanite and Insulator Company subsidiary has completed work on natural fatty acid based esters, which it is marketing under the name of Midel. GEC sees the main market as being for retrofilling existing equipment, where silicone-based products are less suitable. Another ester

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product has been developed by Rhône-Poulenc, in cooperation with the Swedish cable company, Asea Kabel. The fluid is a nonchlorinated ester, benzyl neocaprate. Further possibilities for PCB replacement exist with PAOs. Uniroyal Chemicals has introduced a line of high molecular weight PAO fluids, which are said to be less costly than silicones and have been approved by the fire authorities.

The demand for insulating oils of all types, including mineral oils, is estimated at 150,000 tons in western Europe, covering both the initial-fill and top-up and replacement markets. The expected demand for synthetics, of all types, is thought to be in the 2000-ton range.

6. Cable Compounds

"Cable compounds" designates compounds used for the impregnation of paper-insulated electric power cables and for filling the interstitial spaces in plastic-insulated telecommunication cables. It includes blends of oils (which may be mineral oil or synthetic), and formulations of such blends with additives to achieve particular characteristics, such as higher viscosity and a nonmigratory performance during service. Even in this limited and specialized field there is a wide diversity of compound types. The primary differentiation is between power cables and telephone cables, as follows:

Power cables	Telephone cables
"Self-contained" hollow core cable	"Fully filled" plastic-insulated cables
"Pipe"-type cable	Optical fiber cables
"Solid" cable (mass impregnated; non-draining or viscous liquid)	

It is important to distinguish between "impregnating," as applied to power cables, and "filling," as applied to telephone cables. In a power cable, the compound and the paper together form a composite dielectric, which has properties of insulation greatly superior to what could be achieved with either component separately. The compound forms an integral part of the cable insulation, and in the manufacture of the cable, every effort is made to ensure that no air or vacuous spaces remain in the dielectric when the process of impregnation has been completed.

In a telephone cable it is the extruded plastic around the conductors that forms the primary insulation. The "filling" compound has a secondary insulating function but is introduced primarily to prevent the penetration of water into and along the length of the cable, in the event of rupture of the cable oversheath. Pockets of air can be tolerated within the interstitial spaces of the cable core, provided a continuous channel does not exist along a significant length of the cable. Nationally or internationally agreed quality control tests are applied to manufactured cable lengths, to ensure compliance with specification requirements.

Cables of the hollow fiber type require oils of the lowest possible viscosity, compatible with the need for an acceptably high flash or fire point, to minimize the possibility of fire hazard. Naphthenic mineral oils having a carefully controlled degree of aromaticity are still used for this application, but currently alkylbenzenes are more often specified.

Pipe-type cables utilize a fairly low viscosity oil to transmit the hydraulic pressure within the pipe, but a considerably higher viscosity compound to impregnate the cable cores. Polybutenes have replaced mineral oils to a very great extent in this design. Solid-type cables were traditionally impregnated with blends of viscous oils, to which refined natural resin (colophonium) had been added. This addition resulted in a very greatly increased viscosity at ambient temperature, without unduly increasing the viscosity at cable impregnating temperatures (com-

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monly between 115 and 135°C). In this way problems resulting from compound drainage in service were reduced, while processing times during manufacture could be kept down, in the interests of economics. Polybutenes of approximately 900–1200 molecular weight have been widely used in the past two decades for the same purpose; their disadvantage of high viscosity index has been made good by improved cable manufacturing techniques. However, since the 1960s, by far the greater proportion of solid cables have been impregnated with mass impregnated non draining (MIND) compounds. These can be based either on mineral oils or on polybutenes, to which are added suitable waxes, to obtain a high melting point.

In the telecommunications markets, metallic conductor cables use compounds made from either mineral oil–wax blends, polybutene–wax blends, mineral oils, or block copolymers. For optical fiber cables, the tube or slot filling formulations are based on low viscosity mineral oils–polybutenes or high molecular weight PAOs, gelled with micronized silica. For filling interstitial spaces, wax–mineral oil or wax–polybutene blends are used.

Cable compounds for power and telephone usage are usually formulated by specialists such as Dussek-Campbell (Burmah), BP Chemicals, Exxon Chemicals, Witco, or Schumann. The annual market for traditional compounds is around 24,000 tons in western Europe, and that for optical fiber gels was around 10,000 tons worldwide in 1996. Regarding impregnants and cable oils, the sales of PIBs in western Europe now total over 10,000 tons for these electrical and cable applications, and sales of alkylbenzenes are around 7000 tons. Thus these sectors are of great importance to synthetic base stock producers, the largest single outlet identified for alkylbenzenes.

7. Oil-Based Drilling Fluids

The high temperatures and pressures characteristic of the drilling environment make for significant advantages to the use of oil-based drilling muds; these benefits include good lubricity coefficients, easier drilling through salt, potash, or gypsum, reduced drill point torque and drag, and corrosion protection of the drill pipe. In general, faster drilling, longer bit life, and higher working temperatures are possible. Although oil-based muds use lower amounts of additives and are reusable, there have been concerns about harm to marine life if muds are disposed of at sea. Hence the shrimp test or Krangen–Krangen test, used in the North Sea, to assess the effects of mud oils on sea life.

The range of possible viscosities used in drilling fluids is quite wide, and varies from light mineral process oils through nontoxic gas oils to odorless kerosene. There may just be a chance that completely nontoxic synthetic fluids could find a niche in this market, despite their higher costs. In future any such development is likely also to depend on their biodegradability, thus bringing esters into contention.

At its height the North Sea was using about 50,000 tons of oil bases for drilling muds annually. This figure halved after the 1986 crude oil price collapse, but it then stabilized and is growing again.

8. Circuit Board Fluxes

A new end use for synthetics has been developed in printed circuit board fluxes, where clean burn-off is an essential requirement. PAGs dominate this market. Potential sales are around 5000 tons/year worldwide, with of course strong demand from the Pacific Rim.

9. Mold Release Agents

Mold release agents comprise another hard-to-define market. Mineral oil emulsions have been used as concrete mold release agents for many years. The end use identified here is for mold release in the plastics and rubber industries, where clean lift-off and noncompatibility with the

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rubber or plastic are essential characteristics. PAGs are the most popular product on a price–performance basis, with silicones also competing in this sector, although at much higher prices.

E. Metalworking Fluids

Metal working can be defined as changing the physical dimensions of a piece of metal, referred to as the workpiece. Metalworking operations can be split into two categories, cutting and forming. Cutting is the removal of metal from the workpiece in the form of chips. Cutting operations involve turning, milling, tapping, drilling, and grinding. In forming processes, the workpiece is subjected to enough pressure to cause the metal to flow into a predetermined configuration. Forming operations include hot and cold rolling, drawing, stamping, and coining. In both cutting and forming operations, friction from metal-to-metal contact causes wear and heat generation. Additional heat is generated as metal is stretched and deformed. Excessive heat buildup will result in tool wear and poor surface finish. Metalworking fluids minimize friction by providing good lubricity and remove heat from the tool and workpiece.

The metalworking business in western Europe is very large, at about 360,000 tons of total demand. This is broken down into about 200,000 tons of cutting oils, divided approximately 60:40 into neat oils and soluble oils (as supplied), together with 85,000 tons of rolling oils and the balance in stamping and drawing fluids, quenchants, and protectives. The U.S. market totaled about 319,000 tons in 1995, broken down as follows: 40% metal removal fluids, 24% forming fluids, 8% protectives, 6% heat treatment products, and 22% other products.

Pricing is highly competitive, and synthetics have had a mixed reception in recent years in general-purpose cutting oils. However, one major U.S. synthetic base supplier reported a 40% increase in sales between 1985 and 1990 in the cutting fluids sector. On the other hand, in the more specialized markets of steel and aluminum rolling, drawing, stamping, and quenching fluids, synthetics scored notable successes in the 1980s.

There has been immense concern in the metalworking fluids business in recent years, as numerous accepted formulations, and additives such as chlorine, have come under threat from environmental regulations. Disposal and biodegradability are other major issues. Thus the industry must now concern itself with "cradle to grave" problems, within which performance on the job is only one criterion.

In Sweden, rapeseed-based natural cutting oils were introduced as early as the mid-1980s, by AB Karlshamn. In the 1990s synthetic ester based cutting oils started to be used, notwithstanding the initial costs, owing to their ready biodegradability. Similarly, oil-soluble PAGs will expand their market share for special applications, such as slideway lubricants for machine tools. High molecular weight polybutenes, being completely nontoxic, are another contender.

1. Water-Miscible Cutting Fluids

In the cutting oil field change is constant, and the main favored product currently is semisynthetic; that is, it retains a mineral oil content but contains an array of other products, mainly based around a corrosion inhibitor (CI) additive package. Some of the semisynthetic cutting oils contain up to 20 components, and it is very difficult to persuade formulators to confirm what is being used in the final product. In the 1970s polyglycols were introduced as components for cutting fluids, but technical drawbacks from paint stripping and the removal of lubricants from machine slideways were noted. As a result, synthetics received a poor press in the cutting oil business. The move to semisynthetics in the 1980s was an attempt to rebalance the situation, by again adding mineral oils to the formulation. Nevertheless, it appears that cutting oils are still a target for the synthetics suppliers, with primarily PAGs trying and gaining success, especially for very hard or exotic metals. PAGs, also used by formulators as the lubricity base for

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water-soluble cutting and grinding fluids, work by taking advantage of the phenomenon of inverse solubility, that is, the tendency of a material to become less soluble in water as the solution temperature increases between tool and piece, as it does at the metalworking workface. The PAG comes out of solution and coats/protects the metal surfaces at the critical time.

In addition to components, Union Carbide offers fully formulated extreme pressure metalworking fluids, as well as bases to which can be added fatty acids or phosphate esters. PAGs are also used as coupling agents in CI packs, which represent about 2% of the final fluid.

Another recent development has been the introduction of long chain polyol esters as "neosynthetics." These are used at high levels (30–50%) in the emulsion concentrates, to replace the EP additive, sulfur or chlorine. Such formulations are used for machining hard alloys, like silicone aluminum, and for deep hole or gun drilling applications.

Overall, however, volumes of synthetics sold into this sector remain small, and the bulk of the market remains either with traditional mineral oil emulsions or the multicomponent "semisynthetics," which are mainly complex chemicals, rather than the synthetic base fluids under review here.

2. Neat Cutting Oils

There appears to be no evidence that any synthetic bases are being used to manufacture neat or straight cutting oils. This is a very cost-sensitive market, so the bulk of demand will remain with mineral oils. PIBs or oil-soluble PAGs could be candidates for special formulations.

3. Steel, Aluminum, and Copper Rolling Oils

In steel rolling oils the move toward long chain polyol esters is continuing, and these compounds are expected to totally dominate the steel market in Europe by early in the 1990s. Fundamentally these products are based on trimethylol propane (TMP) or pentaerythritol esters. Earlier formulations were based on emulsifiable oils (70% mineral oil, 25% tallow fats, 5% emulsifiers). The TMP esters were originally developed by Quaker Chemical, but this technology has now been adopted by other specialist suppliers in both Europe and the United States. However, while these esters now have an estimated 90% of the European market, development in the United States has been much slower, and only about 35% of the steel market is currently using long chain esters.

In cold rolling of aluminum foil, where all products used must be nontoxic because the foil is used for food wrapping, the main fluid used for the rolling process is a nontoxic gas oil, mainly produced by solvents companies. Also in wide use are isoparaffinic solvents such as Exxon's Norpar. A single large mill can use 3000 tons of solvents annually. Rolling is at 200–300 m/min at 675°C. The base solvent has a viscosity of 1.8 cSt at 40°C and a boiling range of 200–250°C. Load-carrying and lubricity additives are incorporated, which enable increased reductions to be taken before the lubricants break down. It is known that polybutene is in use as an additive because of its ability to depolymerize and evaporate. Similarly, there is evidence that U.S. manufacturers are using PAGs as an additive/rolling aid at a ratio of 5% of the total solvent.

Additionally, from 1988 to 1991, in foil rolling plants in Europe, PIB-formulated machinery lubricants have been increasing their share of the business, to ensure compatibility and nontoxicity in the event of cross-leakage to the foil.

For copper rolling, the annual demand for fluids is about 15,000 tons in western Europe. Emulsifiable mineral oil–fatty acid blends are used to avoid staining problems due to water, and metal passivators are also added. Fatty acid esters are replacing straight fatty acids. Polybu-tenes have been used for hot rolling of copper, but it is not known whether the products are yet established.

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4. Stamping, Pressing, and Forming Oils

In hot stamping, the primary products used are mixtures of graphite and water, from companies such as Acheson Colloids. The concern of the hot stamping companies is that the use of any kind of mineral product or chemical product will result in a "fire-flash" before the product has actually served its purpose, as a carrier of the graphite to the point of contact. Nevertheless, there is still interest in the possibility of using polyglycols or polybutenes for these applications. More technical work is needed before progress is made, for this is a very conservative industry.

In cold pressing lubricants for sheet metal, it is believed that the traditional special semifluid pastes are still the dominant products, coming from organizations such as the Houghton Group. BP confirms that the company is selling polybutenes for stainless steel pressing, again presumably because of the clean burn-off and nonstaining nature of the PIB. PAGs and PIBs are also being used in automatic cold stamping of components, such as spark plug bodies. The clean burn-off of the products during annealing is a major advantage. Several suppliers have been trying synthetics in recent years for these applications.

In the stamping and forging of aluminum in the United States, the industry has recently been replacing chlorinated paraffins, for environmental reasons. The stamping fluid, of course, must be removed, and here PAGs, which can be water-rinsed, are finding an outlet in preference to products needing washing off with 1,1,1-trichloroethane.

5. Wire and Tube Drawing Lubricants

In the drawing of wire, the products used for many years were based on soaps and fats. Clearly these are now being replaced by more modern and environmentally acceptable products. Some 2500 tons of polyglycols reportedly was being sold into the wire drawing sector in Europe, and this usage for PAGs has also been confirmed in the United States. BP Chemicals also advises that polybutenes are being used in stainless steel wire drawing and also in copper tube drawing. On the other hand, in the production of shaped aluminum extrusions, such as for window frames or patio doors, it appears that water–graphite mixtures are still the norm. These are swabbed onto the ram area of the extruder, not used as a die lubricant.

6. Aluminum Can Stock and Can Drawing Fluids

A number of companies, like Mobil, have strong positions in the specialized markets for aluminum can stock and can drawing fluids. Additionally, specialized formulators like Nalco and Ferro in the United States compete, and some aluminum companies make up their own formulations on site. Nontoxicity and FDA approval are, of course, mandatory. It is known that PAGs are in use in small amounts, as are PIBs. Similarly, long chain polyol esters, emulsified at the consuming plants, are in use for aluminum can stock drawing in the United States.

7. Heat Treatment (Quenching) Fluids

In the quenching fluids sector, attempts by producers of synthetic quenchants to push up their market share continue without abatement. Union Carbide was the first in this sector, with Quenchant A, and subsequently ICI and others moved into the market. Polymer quenchants are much better than mineral oils in environmental terms, because fire hazards are eliminated and less protection equipment is needed. Polymer quenchants also improve working conditions, owing to the elimination of smoke and fumes. Additionally, because these products are diluted with water to an average of 15% (range 10–20%), there are lower initial costs and reduced "drag-out." The main products competing in this market are PAGs, polyvinyl alcohols (PVA), polyvinyl pyrrolidone (PVP), and polyacrylates. There have been a number of problems with PVA and PVP, and the two leaders at present are PAGs and polyacrylates.

Union Carbide's product line has been extended to Quenchants A, B, E, HT, and RL. These

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are sold directly to large users such as GM and Boeing, and to specialized commercial heat-treating companies.

In 1985 total U.S. polymer sales were 18,000 tons, in a quenchant market of 73,000 tons (as sold). By 1995, polymer quenchant sales in the United States had reached 40% of the total (26,000 tons out of 65,000 tons), the balance being mineral oils. About half the total polymers are PAG-based, giving sales of 13,000 tons of PAG-based quenchant fluids (as sold) in 1995.

F. Other Industrial Lubricants

1. Textile Lubricants

Synthetic fibers are polymers of very high molecular weight. The nature of polymers is such that they have very little inherent lubricity. In every stage of their manufacture, from polymerization to production of finished consumer articles, it is necessary to provide lubrication to aid the control of friction. This lubrication is provided as a "spin finish" for primary fiber production. Depending on the end use, this finish may be removed and secondary textile mill finishes provided for subsequent processing and even for point-of-sale handling.

The demands of the textile industry for processing aids to control the fiber friction at different stages of processing are infinite. This has led to a supporting industry providing the necessary expertise, often integrating chemical manufacture, textile evaluation, and blending facilities. For simplicity the requirements can be classified into two main groups:

Spin finishes
Provide the correct balance of fiber-to-fiber and fiber-to-guide friction
Provide static control during polymer spinning and subsequent processing
Seek to provide a product that has optimal thermal stability and volatility characteristics
Give rapid fiber surface wet-out; have good anticorrosive properties
Have good stability at high and low temperatures; have minimal effect on the fastness of dyes and pigments
Are easy to remove in washing off baths
Textile mill finishes
Provide correct frictional and static control, as with spin finishes
Provide effective control for a full range of natural and synthetic fibers and blends
Provide efficient performance in a range of textile operations
Are compatible with other processing aids both within the system and with spin finishes
Can be easily removed and have no adverse effect on the dyeing or dye fastness ratings
Do not leave deposits that are difficult to remove or interfere with machine performance
Are stable over a wide range of temperatures and have an extended shelf life

Originally white mineral oils were widely used for this application. PAGs have now taken over from white oils almost completely, because of their controllability (via molecular weight) and water solubility. PAGs are used mainly in nylon and polyester finishes. Probably 90% of PAG consumption is in this area rather than in wool or natural fibers. There are no figures available on actual PAG consumption within the many finish formulations.

Worldwide, including the countries of the former Soviet Union, about 180,000 tons of spin and textile mill finishes were estimated to have been used in 1996. Around 35,000 tons was used in the United States. Western Europe consumed around 25,000 tons and the Pacific Rim about 40,000 tons in 1996. A large number of specialized companies, including Akzo, BASF,

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CEC, Croda, Henkel, Hoechst, Castrol, Montedison, Shell, and Unichema are involved in this business, together with small specialist formulators.

2. Wire Rope, Chain, and Chain Saw Lubricants

Industrial chains are often working under severe conditions of heat, in textile works (stenter chains), in car factories, or in pottery and glass kilns. Large chains are mainly used in conveyor systems, but the difficult applications are mainly those involving severe heat from ovens. Such high temperature conveyor bearings have always presented a difficult lubrication problem. Often molybdenum disulfide carrying products have been used. PAOs, PIBs, and trimellitates are now proving successful for temperatures up to 200°C. Some U.S. manufacturers also market ester-based products for this application, for use up to 280°C. One major supplier estimates a total of 1000 tons of U.S. sales of synthetics into "hot" applications, such as ovens, glassworks, stenters, and conveyors.

Although the PAGs enjoy a broad industrial market, increased usage of synthetic alternatives is expected in future. Poly(α-olefins) and PAO–ester blends are the most likely competitors. It is believed that sales of synthetics in these sectors of the industrial market have increased significantly over the past few years as a result of major sales efforts, especially by Mobil, and total annual sales in western Europe may be around 10,000 tons.

Similarly, for forestry chain saw oils, long chain esters are used together with diester-based two-stroke oils, for the chain saw engine. Polybutene-based products are available for "high tackiness" applications on overhead conveyors in car plants, where drip-off would be unacceptable. Polybutene-based products are also now in use in wire rope lubricant formulations which traditionally have been bitumen based.

3. Food-Grade Oils

For many years white mineral oils have been used for direct food contact applications, a high volume example being dough-knife lubricants in bakeries. A large bakery can use 50–100 tons/year of white oil. Similarly, for accidental or occasional food contact applications, white oils have been used, as mentioned earlier, for LDPE compressors.

In 1990 in the United Kingdom a temporary ban was imposed on the use of white oils in direct food applications, as a result of tests that found retention of white oils in animal tissues. The ban was rescinded, but the issue is not yet resolved. Concern also revolves around naphthenics in some hydrogenated white oils and their interaction with bread bleaches, to form polychlorinated biphenyls. If the white oil ban is reimposed, a new market for synthetics may open up. However low cost competition from natural vegetable oil esters, such as rapeseed oil, is likely to secure the bulk of the direct food application market, rather than synthetics. As an indicator of volumes, worldwide white oil consumption in 1996, for all applications (including cosmetics, personal care products, agricultural spray oils, pharmaceuticals, papermaking, or fiber batching) totaled around 900,000 tons. The direct food applications include bread making, rice polishing, "glossing" of fruit and bread, and, it is believed, dedusting sprays used in grain conveyors in the United States, where white oils are currently used.

Lubricants based on PAGs, PAO, and PIB can be formulated to pass FDA tests. Union Carbide offers a range of fully formulated PAG-based extreme pressure lubricants for food machinery, where accidental contact can occur. All components can be identified in the FDA Regulations as set forth in the U.S. Code of Federal Regulations [21 CFR 178.3570(a)]. In addition to providing nontoxicity, better lubricity, higher VI, and oxidation and thermal stability, the lower pour points and viscosities have led to energy saving of up to 8%, compared to white oils or mineral oils, in food machinery gearboxes. As discussed earlier in connection with alumi-

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num rolling, lubricants for machinery rolling foil represent a growing outlet for PIB-formulated lubricants. PAO producers are also attempting to enter into the food-grade markets at present.

G. Greases

Higher performance greases, based on synthetics of all types, PAO, PAG, PIB, and polyol esters (all chain lengths), are now being promoted widely. Polyurea greases are ideally suited for rolling bearings operating in high temperature, high speed conditions, particularly if the grease is ester-based. Kluber has developed both full synthetic and part synthetic ester-based polyurea greases specifically for bearings operating under arduous conditions. Lithium soaps can also be used for synthetic greases, as can PAOs, PAO-VHVI, blends and PAO–ester blends. Hatco has a polyol ester grease (HATCO 3000) for use on stenter frames and other applications with operating temperatures of up to 280°C.

Many grease manufacturers believe that the total market for greases will remain static, with increasing demand in some industries and regions being offset by the ever expanding use of sealed-for-life bearings and longer life products that substantially lengthen relubrication intervals. These trends inevitably mean the use of greater amounts of synthetic fluids in grease manufacture, which has been confirmed in the latest worldwide surveys conducted by the U.S. National Lubricating Grease Institute (NLGI). Synthetic, highly water-resistant greases are also being introduced. Amsoil launched such a product, which is believed to be a calcium soap grease with a PAO base, in July 1996.

Environmental issues are also having an increasing influence on grease users. The trend is most evident in Europe, where biodegradable greases are growing in popularity, particularly for outdoor use in agricultural, mining, forestry and other off-highway equipment. Long chain polyol esters and vegetable oil esters appear to be the preferred bases. High oleic acid content vegetable oils, such as those developed by Lubrizol, are being used increasingly.

Rocol launched a calcium soap biodegradable grease, Biogen Ropeguard, with a polyol ester and modified rapeseed ester base blend, in April 1996. Two other biodegradable products were also introduced. Biogen Slidechair is a calcium soap, modified rapeseed oil, and synthetic ester based grease with a small amount of graphite, and Biogen Open Gear Spray is a calcium soap grease containing graphite and molybdenum disulfide in a vegetable oil base.

Automotive greases were covered above (Section V.A), and aviation greases are the subject of the next section.

H. Aviation Lubricants

1. Civil Aviation Lubricants

The bulk of civilian aviation lubricant demand is for gas turbines in jet aircraft, followed by aviation piston engine oils. Development costs for jet lubricants are extremely high, as are the costs of flight tests. Effectively, only Castrol, Esso, Mobil, Nyco, and Shell remain in the aviation gas turbine business, even BP having withdrawn in 1980, as others did in the 1970s.

The first generation of gas turbine lubricants, known as type I oils, were of 3 cSt viscosity, mainly based on diesters, principally azealates and sebacates. One other earlier type of lubricant (the type I, 7.5 cSt oil) was thickened with a polyalkylene glycol. This product was used primarily in turboprops, to combat the heavier loadings. The civil turboprop aircraft that used type I oils are now mainly phased out, except for a few Viscounts, plus of course HS748s and Fokker F27s, used on regional routes. In western Europe most aircraft now use type II or type III oils, which are all based on polyol esters and are of 5 cSt viscosity.

Diester-based type I oils are still in use, at a level of about 1500 tons/year in Europe, for

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both civil aircraft as mentioned and for aircraft retained by the military (such as the VC10 or the Buccaneer). Additionally a good proportion of diesters are used in jet engines for generating, gas pumping, or industrial use, such as the Rolls-Royce Avon. Almost no diesters are in use now in the United States. Esso and Mobil are the market leaders in jet lubricants, so over 70% of the gas turbine lubricants used in western Europe are actually imported from the United States in finished form. Exxon's major blending plant is in Bayway, New Jersey, and Shell, Nyco, and Castrol blend in Europe. The leading base ester suppliers in the United States are Hatco and Mobil, followed by Emery (now Henkel), while in Europe, Unichema, Ciba-Geigy, and Nyco are the main producers of esters approved for aviation usage. Nyco is a major supplier to the French air force, and also a significant exporter of synthetics to the CIS.

In the piston engine aviation market, which is of course dominated by engine lubricants for small light aircraft, high quality single-grade mineral oils have been preferred for many years. However, Shell introduced a PAO–mineral oil multigrade (Aeroshell Oil W 15W-50), which is understood to be enjoying increasing popularity, with U.S. sales of over 1500 tons/ year (i.e., 30% of the total demand of 5000 tons) as of 1990.

In the field of aircraft hydraulics, civilian aircraft are using specially developed types of fire-resistant phosphate ester in their hydraulic systems. Monsanto and Chevron of the United States are the two suppliers to this market sector on a global basis. The requirement is for phosphate esters capable of operating at very low temperatures. Monsanto makes alkyl–aryl esters in-house at Bridgeport, New Jersey, and possibly in St. Louis. Chevron offers mixed triaryl–trialkyl esters. Total demand for phosphate esters is believed to be about 3000–4000 tons. Military aircraft tend not to use fire-resistant hydraulic fluids, but have been switching from naphthenic mineral oils to PAO–ester blends, following losses in action in Vietnam due to fires from hydraulic leakages.

The overall demand for "aviation" hydraulic fluids worldwide is estimated at about 15,000 tons, including the countries of the former Soviet Union. About half this demand is mineral oil, and it should also not be overlooked that "aviation quality" or "superclean" and military specification fluids are demanded for ground equipment, and even in earthmoving equipment, by nonmilitary organisations.

Aviation greases are of course made to the same stringent standards as other products for the aircraft industry, and they must withstand the same extremes of temperature. A number of companies are offering greases using PAOs or esters as bases, and these are proving to be increasingly successful in this demanding market. Despite its intrinsic appeal, the aviation business does not utilize large volumes of lubricants. The lubricants in gas turbines are rarely changed, but are simply topped up at the end of long flights, so that there is a continual renewal of the charge. Additionally, one British company has Rolls-Royce approval to recondition gas turbine lubricants. A small but steady business exists in recycling and reconstituting used gas turbine lubricants and returning them to their owners, all over the world.

It is estimated that the total annual consumption for both military and civilian aviation is in the order of 70,000 tons, split as follows: 45% for gas turbine oils, 25% for piston engines, 25% for hydraulic fluids, and the balance of 5% for greases, compounds, and miscellaneous uses.

2. Military Aviation Lubricants

Practically all military lubricant applications are covered by specifications, issued by the United States (Mil-L, etc.), the United Kingdom (DEng), France (AIR), or Russia, with NATO codes also available as a cross-reference.

Obviously many synthetic products, such as gas turbine lubricants, are common to both civilian and military uses. However there are differences in specifications and usage: for exam-

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ple, the U.S. Air Force prefers to use a 3 cSt polyol ester, while most civilian aircraft and the U.S. Navy prefer 5 cSt. There are signs of change here, however, and a new 4 cSt polyol ester specification is to be introduced soon. So far, Castrol (with Castrol 4000) is the only approved supplier. The U.S. Army has a tank, the Ml Abrams, which is the only one in the world with a gas turbine engine. This vehicle has a requirement for a polyol ester lubricant meeting the Mil-L-23699D specification.

A further long-standing but small U.S. Army requirement has been for an arctic engine oil (Mil-L-46167). A product meeting this specification was in great demand during the development of the Alaskan oil fields, but since those days sales have dropped sharply. The predominant formulation used was a dialkylbenzene-based lubricant, supplied by Conoco (Du Pont); however, the specification can also be met with a 70:30 PAO–ester formulation.

PAO-based formulations have also been in use for several years in military hydraulic fluids for aircraft (Mil-H-83282) and ground equipment (Mil-H-46170). Sales of these fluids were around 12,000 tons in 1996, worldwide. The 83282 specification replaces the naphthenic mineral oil spec. (Mil-H-5606) and is known to be used in F14, F16, and F/A18 fighters of the U.S. Air Force, Navy, and Marines. The formulation is a mixed 65:35 PAO–diester, but it is believed that a polyol ester may be introduced soon. The 46170 specification formulation includes rust inhibitors, for tanks and other ground equipment hydraulics, to be used when the units are in storage.

Additionally, PAO and esters have been introduced for instrument applications, where the recognized specification is Mil-L-6085A. Avionics uses include dielectric heat transfer fluids, used in closed systems for radars and electronic counter measures (ECM) systems. A U.S. Air Force specification (Mil-C-87252) calls for a 2 cSt PAO for these applications.

A wide range of military greases for aviation has been specified, including those with NATO codes such as G382 based on mineral oils (−40 to 120°C operating range), or silicones and perfluorosilicones (G372 and G398). As far as synthetics are concerned, G354 is a diester-based grease (−75 to 120°C operating range), G395 is a nonsoap PAO-based grease (−55 to 175°C operating range), and G363 is a complex, hydrocarbon-resistant ester-based grease.

Finally, mention should be made of the CIS, which surprisingly has used large volumes of naphthenic mineral oils for aircraft gas turbine lubrication for many years. However, the CIS also has a polyol ester specification, B-3V for a 5 Kinematic Viscosity (100°C) lubricant, and VNII-NP-50-1-4-U for a 3.2 KV diester-based lubricant, as well as IPM-10 for a 3 KV diester–synthetic hydrocarbon blended product.

VI. FUTURE TRENDS

The market for automotive engine oils has been through a period of unprecedented change in terms of industry specifications, product development, and customer expectations at a time of low overall growth in demand for products. This has caused problems of profitability for additive manufacturers and base oil producers, in addition to opening up opportunities for companies with marketing and service support skills. The primary observation is that suppliers with higher performance products, better marketing, and special attention to service support are more likely to take market share from suppliers that lack one or more of these customer-driven attributes.

The drivers for changes to engines are government regulations on fuel economy, emissions, noise, and recycling, coupled with consumer needs for affordability, performance, drivability, durability, and styling. These drivers lead to changes in engine, fuel, lubricant, and other material technologies. Regulatory compliance is now regarded as an entry price for vehicle manufacturers, while meeting consumer's desires is seen as the way to product differentiation, increased market share, and higher profits.

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The changes in engine design technology are typified by the General Motors "World Engine," to be introduced in 2000, with 800,000 to be built in North America and Europe, in multiple configurations (four-cylinder, double overhead camshaft, with 2- and 4-valve-per-cylinder variants in 1.8-, 2.0-, and 2.2-liter capacities). The development costs are expected to be $1.3 billion. At the same time, the Toyota D-4 engine is being engineered for improved performance with ultralow fuel consumption, higher output, quicker response, and lower emissions. It has high pressure, fuel swirl, direct injection, helical intake ports, variable valve timing, exhaust gas recirculation and storage reduction catalysts for oxides of nitrogen (NO_x).

The replacement of current tests for proof of performance testing and the development of the next engine oil specifications (ILSAC GF-3, API PC-7, and PC-9) are the main issues for the immediate future. GF-3 was proposed in early 1995, as an oil specification to reduce emissions, to protect emission control systems, to further improve fuel economy, and to give protection during extended drain intervals. Further definition, mainly in terms of reductions in volatility (for oil consumption control), enhanced fuel economy, and significantly higher performance level were proposed in late 1996. The primary difficulty in deciding how best to achieve these aims has entailed the costs of developing new tests to determine the levels of performance and their correlation with practice. It has been estimated that the installation of new test facilities could cost $25 million, while precision testing could cost another $5 million.

The result has been that funding for the new program was not agreed until mid-1997, and matrix testing did not start until later. The ASTM expects to be able to ballot members about the test results toward the end of 1998, to approve the new tests during 1999, and to have the first GF-3 oils approved by 2000 at the earliest.

In Europe, the ACEA specifications were introduced in January 1996. These replaced the Comité des Constructeurs du Marché Commun (CCMC) specifications and included five new tests. ACEA is now requesting "ACEA-98" specifications, with significant changes and improved product performance. Association Technique de l'Industrie Européenne des Lubrifiants (ATEIL) and Additive Technical Committee (ATC) are, however, questioning the need and timing for these changes, as well as the process to be used for the new categories. The new categories requested are B4, for direct injection passenger car diesel engines with 30,000 km oil drain, and E4 for superhigh performance diesel engine oils, to meet the MB 441LA test requirements. Other new ACEA tests could include some of those proposed for GF-3, including fuel economy, OPEST (oil protection of emissions system test, BRT (ball rust test), and Cummins M11.

The next North American heavy-duty diesel engine test will be PC-7 (CH-4). The main reason for the new specification is that mandated reductions on NO_x emissions from diesel engines cause an increase in soot in the engine oil. As a result, the PC-7 specification will have three new engine tests: Caterpillar 1P for steel and aluminum piston deposits, oil consumption, and oil oxidation; Mack T-9 for ring and liner wear; and Cummins Ml 1 for crosshead wear, oil sludge, and oil filter pressure drop. To these will be added tests for shear stability, elastomer compatibility, volatility, and corrosion.

The CH-4 category was defined during 1995, when reference oils were also selected. Precision testing was due to be completed in 1996, as was the ASTM ballot. The timetable for the development of CH-4 was not met, mainly because of delays in test development. API-licensed products were expected to appear early in 1998, but may not be introduced until 1999. In addition to the industry standards, other OEM-specific approvals such as Mack, will continue. Mack plans to issue a new approval list, EO-M, and Cummins is reported to be considering the introduction of a new list of approved premium specification heavy-duty diesel (HDD) oils.

In Japan the national automakers' association, JAMA, has requested a new API category for HDD oils, for use in diesel engines operated in Southeast Asia. JAMA is concerned that

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the PC-7 requirements could lead to low ash oils, counter to the Japanese industry's desire for higher ash oils. The requested category would be PC-8, and it would be aimed at diesel engines with lower piston temperatures and greater use of slider followers, hence greater need for wear protection.

Overall growth in markets for industrial lubricants is likely to continue to be relatively slow for the foreseeable future. World GDP and inflation rates are becoming lower, so increases in demand for industrial lubricants in Asia, South America, and central Europe are likely to be substantially offset by decreases in demand in western Europe and North America.

Quality and performance are likely to be the key to higher prices and product differentiation in industrial lubricants. However, higher quality and performance are likely to lead to further increases in product lifetimes, extended drain intervals, lower maintenance and downtime, and reductions in lubricant volumes.

The trends toward industrial lubricants mat can operate at lower ambient temperatures, which have been most noticeable in outdoor gear and circulating, compressor, and hydraulic systems, are expected to continue, although more slowly than over the last 4 years. In the medium term, the market for low-temperature lubricants and fluids is not expected to expand greatly, but in the longer term the need to unlock the natural resources in the subarctic and possibly Antarctic regions will expand this niche area.

The dominant environmental issues for industrial lubricants (and to a lesser extent for automotive lubricants) over the next 5 years are likely to be:

Biodegradability and bioaccumulation
Toxicity
Waste, disposal, and recyclability

As far as synthetic lubricants are concerned, longer service life means less waste and less total material to dispose or recycle. More highly stable synthetics may be easier to recycle, because the levels of additives are much lower. The more biodegradable vegetable oils may be less easily recyclable, a factor that could eventually favor synthetic fluids.

There is likely to be a greater use of PAOs and PAO–mineral oil blends in land-based gas turbines. Larger, heavy-duty power generating gas turbines will be favored in many parts of the world in which natural gas is readily available (e.g.) large parts of western and central Europe, Asia, and South America, particularly Chile and Argentina). The trend toward higher gas temperatures for greater thermal efficiency will continue.

In industrial gearboxes, there is likely to be an increasing use of synthetic lubricants, but PAOs are unlikely to grow as fast as PAGs. The main reason for this, despite the favorable reductions in operating temperatures and power consumptions for fluids of both types, is the sludge problems experience by PAO-based fluids in gear systems exposed to moist operating conditions.

With rotary screw air compressors, the use of PAOs is likely to increase, although the competition from VHVI oils is likely to increase as well. Unfortunately, this is not a large market in total. There is unlikely to be any significant change in the use of PAOs in refrigerating compressors.

Last, but by no means least, it is likely that lubricant suppliers in the future will pay more attention to customer needs and improved marketing methods. A key factor in determining success is likely to be benefit selling, whereby genuine partnerships between lubricant suppliers and lubricant users allow both to share in the financial rewards obtainable from using higher quality and performance industrial lubricants.

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